**Design Engineering**

# Commutating design for IC amplifiers virtually eliminates offset errors

Commutating auto zero, a new design concept for monolithic operational and instrumentation amplifiers, dramatically reduces initial input offset voltage and offset drift with changes in temperature and time. Dubbed CAZ, the new approach combines digital and linear techniques to bring down initial offset to a low 1 to 5 $\mu$V and hold offset drift to a mere 0.005 $\mu$V/°C and only 0.2 $\mu$V/year. Moreover, the CAZ design permits high-performance monolithic amplifiers to be fabricated with standard low-cost complementary-MOS processing.

The first CMOS chips to employ the CAZ technique include: a pair of operational amplifiers (the compensated ICL7600 for applications requiring voltage gains from unity to about 20, and the uncompensated ICL7601 for voltage gains greater than 20); and two instrumentation amplifiers, the ICL7605 and the ICL7606.

For the CAZ op amps, input offset voltage is three orders of magnitude lower than that of traditional monolithic bipolar op amps, like the 741. Similarly, compared to conventional instrumentation amplifiers, which require highly accurate resistor matching and tracking for their popular three-amplifier design, the CAZ instrumentation amplifiers eliminate the need for on-chip resistor trimming. The CAZ instrumentation amplifiers are intended for low-frequency applications that require voltage gains from 1 to 1000 and bandwidths from dc to 10 Hz.

## How CAZ works

With the CAZ approach, on-chip analog switches connect two internal op amps between two modes of operation—when one amplifier is processing the input signal, the other is in an auto-zero mode. The commutation frequency is the rate at which the two internal op amps are switched between the two modes.

In the auto-zero mode, an external capacitor stores a voltage equal to the input offset voltage plus the low-frequency instantaneous noise voltage. In the signal-processing mode, this capacitor is connected in series with the overall amplifier's noninverting input

to cancel both the input offset and the instantenous low-frequency noise voltage.

The CAZ principle is perhaps best understood by examining the way it is implemented in the 7600/7601 op amps. These devices contain all the necessary analog and digital circuitry on-chip, including two op amps, an oscillator counter, level translators and analog switches. The only external components required are two auto-zero capacitors.

## All about the CAZ op amp

Fig. 1a shows the CAZ op amp as it sequences through its two internal states. In addition to the regular inverting and noninverting inputs, the CAZ op amp has a third auto-zero input, designated AZ. In most applications, this auto-zero input will be connected to system ground, although it may be connected to the noninverting input for improving common-mode rejection ratio.

Because capacitors $C_1$ and $C_2$ must have high values between 0.01 and 1 $\mu$F to minimize offset errors due to charge injection they are not suitable for monolithic integration. On the other hand, since resistors $R_1$ and $R_2$ have values of about 100 k$\Omega$ each, they can easily be fabricated on-chip.

As long as the commutation frequency is high compared to the leakage discharge times of $C_1$ and $C_2$ for the signal-processing mode, an input signal will be processed as though the CAZ op amp were a single amplifier. The discharge time constants of $C_1$ and $C_2$, when each has a value of 0.2 $\mu$F, are in the tens to hundreds of seconds.

During the auto-zero mode, with a suitable choice of values for the resistors and the capacitors, each internal op amp is connected, in turn, into a unity-gain mode for frequencies approximately equal to or less than the commutation frequency. As a result, besides the dc offset voltage, each capacitor acquires a voltage equal to the instantaneous low-frequency noise below the commutation range of the internal op amps. In addition, the low-pass filter networks formed by $R_1$ and $C_1$, as well as by $R_2$ and $C_2$, attenuate high-frequency noise above the commutation frequency at 6 dB/octave.

This unique characteristic of the CAZ op amp to reduce, not only the dc offset voltage, but also the low-

MODE A : A1 PROCESSING INPUT SIGNAL    MODE B : A2 PROCESSING INPUT SIGNAL

(a)



(b)
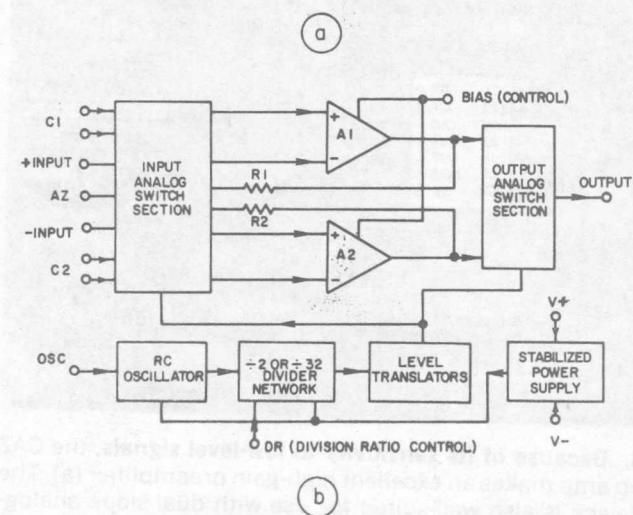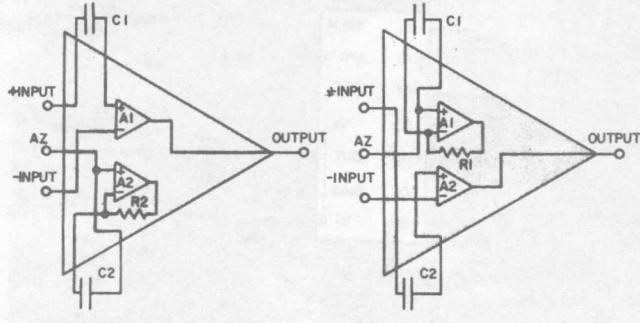
**1. In the CAZ op amp, analog gates switch two internal op amps** between signal-processing and auto-zero modes to cancel offset errors and instantaneous low-frequency noise (a). In addition to this analog circuitry, the CMOS chip has digital circuitry, which includes an RC oscillator,for controlling the commutation frequency(b).

frequency noise below the commutation frequency has at least two very important implications:

■ The CAZ op amp can approach a near-zero noise figure for frequencies from dc to about one-tenth the commutation frequency. For good noise performance below 10 Hz, the commutation frequency for the 7600/7601 should be between 30 and 200 Hz.

■ The low-frequency or flicker noise of the input transistors of the internal op amps is less critical than that for a conventional op amp. This is very convenient, because the input transistors for the CAZ op amp are MOSFETs, and their flicker noise is about five times worse than that of bipolar transistors or junction FETs.

As Fig. 1b illustrates, the 7600/7601 op amps actually consist of three main functional blocks: a full complementary set of input and output analog switches for connecting the internal op amps into their two modes of operation; a digital section containing an RC oscillator, a divider chain and the necessary drivers for the analog switches; and an analog section comprising two internally-compensated CMOS op amps plus their feedback resistors ($R_1$ and $R_2$).

In the switching section, six analog gates switch each internal op amp between the signal-processing mode and the auto-zero mode. The RC oscillator in the digital section operates from a low-voltage internally regulated supply. The oscillator output may be directed, by means of the DR terminal, either through a 5-bit (divide-by-32) counter or a single-bit (divide-by-2) counter. The level translators provide full-supply voltage swings and break-before-make signals to the input and output analog switches. This arrangement gives the user considerable flexibility in controlling the commutation frequency.

With the OSC terminal open-circuited and the DR terminal connected to V+, the commutation frequency is about 160 Hz. To lower it, the designer can add capacitance to the OSC terminal or use an external clock to drive this terminal with a signal of −5 V peak-to-peak, referenced to V+. The oscillator may be stopped by connecting the OSC terminal to ground. To increase the commutation frequency above 160 Hz, the designer should connect the DR terminal to the GND supply. For an open-circuited OSC terminal, this connection gives a commutation frequency of 3.2 kHz.

In the analog section, the CMOS op amps each have two gain stages. By varying the biasing of these internal op amps, the user can select slew rate and unity-gain bandwidth. For example, at maximum bias, the slew rate is about 2 V/$\mu$s, unity-gain bandwidth is 1 MHz, and the minimum guaranteed stable closed-loop gain with any capacitive load is 10.

## The CAZ instrumentation amps

Delivering equally impressive performance the 7605/7606 CAZ instrumentation amplifiers, are true differential amplifiers, capable of amplifying a differential input signal (within the power-supply range) in the presence of large common-mode voltages and referencing the output signal to system ground or some other voltage. An important advantage of these CAZ instrumentation amplifiers over traditional bipolar devices is the automatic self-compensation for offset error voltages, whether they be steady-state, temperature, supply voltage, or long-term variable in nature.

Both CAZ instrumentation amplifiers are low-frequency devices, useful to perhaps as high as 20 Hz, although more commonly used in applications requiring less than 10 Hz. Unlike conventional differential instrumentation amplifiers, the CAZ devices have approximately constant input equivalent noise voltage, input offset voltage and drift values, as well as 100-dB common-mode and power-supply rejection ratios—independent of gain.

As Fig. 2 shows, the CAZ instrumentation amplifier has four functional blocks, three of which are identical to those of the CAZ op amp. The fourth functional block is a differential-to-single-ended unity-gain voltage converter, which consists of a group of eight analog switches plus two external capacitors.
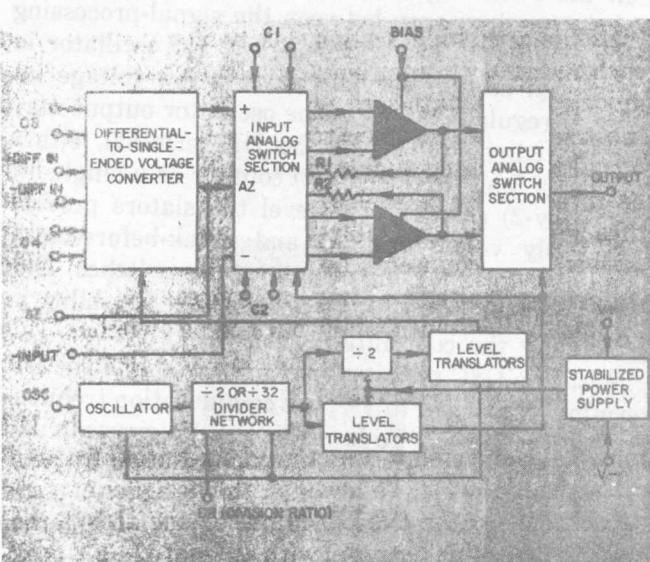
2. **The CAZ instrumentation amplifier** works well at bandwidths up to 10 Hz. It has four functional blocks—the analog, digital and switching sections of the CAZ op amp, plus a differential voltage converter.

When one of these capacitors is connected to the differential signal source, the other is connected to system ground, or a reference voltage, and to the input of one of the internal op amps. A short time later, the connections of the two capacitors are reversed. Thus, at all times, the differential input source is being sensed and applied to one of the internal op amps. The only external circuitry required are two resistors, to set the gain, and four capacitors—two for the internal amps and two for the voltage converter.

Of the eight analog switches in the voltage converter, only four are conducting at any one time. These are the four that connect one of the capacitors to the differential input and the other to ground, or a reference, and to the input of an internal op amp. This aliasing scheme preserves frequency information up to the commutation frequency. Above it, an input signal is transformed to a lower frequency at the output. Because of charge-injection phenomena at the switches and at the output to the voltage converter, the values of capacitors $C_3$ and $C_4$ must be about $1\mu F$ to preserve signal accuracies to within 0.01%.

### Applying the CAZ op amp

The principal application for the CAZ op amp is expected to be amplification of low-level signals from dc to 50 Hz, such as those produced by thermocouples. The CAZ op amp also is well-suited for use with dual-slope analog-to-digital converters. The device's low noise permits sensing signal levels as low as 10 $\mu V$.

Fig. 3a shows a typical application—a preamplifier having a fixed gain of 100. Here, the 100-k$\Omega$ series input resistor and the 0.01-$\mu F$ capacitor protect the CAZ amp from damage even with overload voltages as high as $\pm 1$ kV.

In Fig. 3b, the CAZ op amp teams with the ICL7109 12-bit dual-slope a/d converter, which is designed for
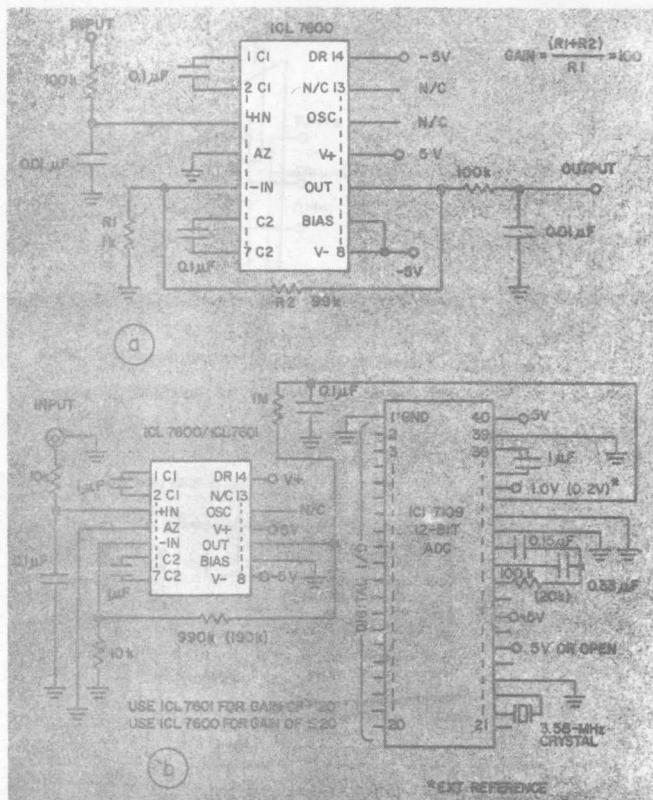


3. **Because of its sensitivity to low-level signals,** the CAZ op amp makes an excellent high-gain preamplifier (a). The device is also well-suited for use with dual-slope analog-to-digital converters (b).

interfacing with microprocessors. The 7600/7601 and the 7109 use the same power supply of $\pm 5$ V, and the entire system typically consumes just 2.5 mA of current.

The input signal is applied through a low-pass (150 Hz) filter to the CAZ op amp, which is connected in a noninverting-gain configuration of either 20 or 100. The internal oscillator of the 7600/7601 runs at about 5.2 kHz, resulting in a commutation frequency of 160 Hz, with the DR terminal connected to V+. The error-storage capacitors, $C_1$ and $C_2$, are 1 $\mu F$ each, for a good compromise between the minimum equivalent input dc offset voltage and the smallest value of low-frequency noise.

The output signal also passes through a low-pass filter (1 M$\Omega$ and 0.1 $\mu F$), having a bandwidth of 1.5 Hz. This results in an equivalent dc offset voltage of 1 to 2 $\mu V$ and a pk-pk noise voltage of 1.7 $\mu V$, referred to the input of the 7600. The output of the low-pass filter directly feeds the input of the converter.

The values of the converter's integrator resistor and the reference voltage must be chosen to suit the overall sensitivity of the system. For example, for a full-scale reading of 2.048 V (0.005 V/count times 4096 counts), the reference should be 1.024 V, and the integrator resistor 100 k$\Omega$. With an amplifier gain of 100, the system sensitivity will be 5$\mu V$/count (0.005 V/count divided by 100).

Alternatively, the gain of the 7600/7601 can be reduced and different values used for the reference
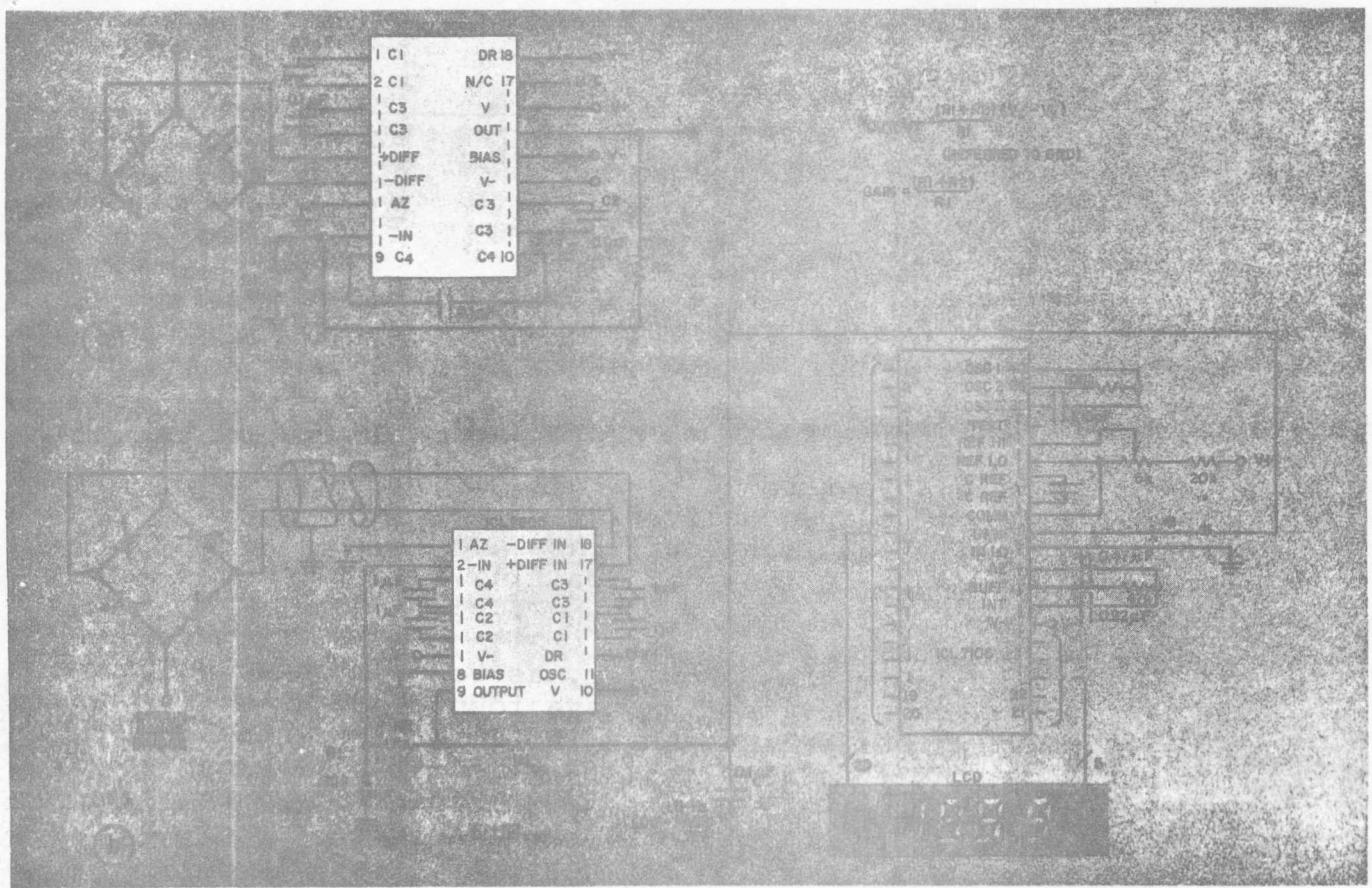
**4. In low-frequency applications,** the CAZ instrumentation amplifier can replace its more costly hybrid or monolithic counterparts. It easily senses bridge voltages (a) for building a digital-readout torque wrench (b).

voltage and the converter's integrator capacitor. With a 190-kΩ feedback resistor, a 0.2-V reference and a 20-kΩ integrator resistor, the gain of the CAZ amp reduces to 20, and the converter sensitivity increases fivefold—for the same output sensitivity.

### Ideal for low-frequency tasks

In low-frequency applications with bandwidths from dc up to 10 Hz, 7605/7606 CAZ instrumentation amplifiers can replace almost any of today's more expensive hybrid or monolithic instrumentation amplifiers. Since the CAZ devices do not require periodic adjustment and have extremely low offset drift, they perform particularly well in adverse environments where it is difficult to service equipment.

One application for the 7605 is measuring the voltage across a bridge network, as illustrated in Fig. 4a. The input common range for the amplifier's +DIFF and −DIFF inputs cannot exceed the supply-voltage range, which might be, say, ±5 V. No adjustments are necessary, except for the gain resistors. In such a circuit, common-mode rejection ratio is typically 100 dB, and the commutation frequency about 50 Hz.

A more specific application for the 7605/7606 CAZ instrumentation amplifier is in a strain-gauge system, like the digital-readout torque wrench of Fig. 4b. In this application, the CAZ amp serves as a pre-amplifier, converting the differential voltage output from the bridge to a single-ended voltage reference to ground. The 7605/7606 then applies the signal to the input of a panel-meter chip—in this case, the ICL7106 dual-slop a/d converter for a 3-½-digit liquid-crystal display. This system employs the internal voltage reference of the converter, instead of an external reference source.

Setting a full-scale reading requires knowing the voltage sensitivity of the strain-guage bridge and then choosing both an appropriate gain for the CAZ amplifier and an appropriate value for the reference voltage. The proper amplifier gain should produce an output swing of about 0.5 V at full scale. The reference voltage required is one-half the maximum output swing, or 0.25 V. Once designed, this type of system requires only one full-scale adjustment—either the amplifier gain or the reference voltage. Total current consumption of the system, less the current drain of the strain-gauge bridge, is about 2 mA.■■